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Three-dimensional surface reconstruction for cartridge cases using photometric stereo

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Abstract

In forensic science, automated firearms identification is an important and yet unsolved problem. On the way to the solution, one of the most important phases is data acquisition. To be able to identify firearms in a reliable way, all the striated and impressed marks on metallic surfaces of cartridge cases should be visible. But two-dimensional images of cartridge cases are very sensitive to the type and direction of the light source(s). Depending on illumination conditions, the images of marks change drastically and sometimes they simply disappear. But, if the three-dimensional (3D) topography of the surface is obtained, the geometry of the marks, which is independent of the illumination, is available. Thus, by providing illumination independent features that can be used for automated matching, 3D data have the potential to make automated matching much reliable. In the literature on data acquisition for automated firearms identification, a few different ways of three-dimensional surface extraction are described, like laser interferometry or laser profilometry. This study presents a real life application of another method, photometric stereo, for the acquisition of 3D topographic data for cartridge cases, which is the one used in BALISTIKA Ballistics Image Analysis and Recognition System. In order to construct 3D topographic data, first of all, two-dimensional images were acquired using a specially designed set-up. After the images were calibrated radiometrically, photometric stereo method was applied. In order to minimize the low-frequency errors in the final surface, a surface-fitting algorithm was used. The method uses low-cost equipment and image acquisition is not time-consuming. Results were compared to interferometric measurement values for error assessment.

Keywords: Automated firearms identification; Photometric stereo; Three-dimensional surface reconstruction; Cartridge cases; CCD imaging

1. Introduction

Firearms identification is the art and science of matching cartridge cases and bullets fired from the same firearm, based on the characteristic striation marks and impressed marks left by the gun. In forensic science, automated firearms identification is an important and yet not totally solved problem. Since many laboratories have to cope up with huge amount of firearm evidences (bullets and cartridge cases), the automation of the acquisition and identification process by a reliable way is very essential. Automated firearms identification systems can help firearms examiners to overcome the cumbersome task of analyzing vast amount of cartridge cases and bullets. Several such systems are commercially available. However, the recognition performances need to be increased and the length of time needed for data input and search need to be reduced to be able to cope with increasing demand for fast and reliable matching.

One of the first and most important phases of automated cartridge case identification is the data acquisition phase. The matching of bullets and cartridge cases is possible thanks to the fact that each individual firearm leaves unique marks on the evidence, due to imperfections and irregularities on its surfaces that get in contact with the cartridge case and bullet. In order to achieve a high recognition performance, the data containing the marks on the surfaces should be obtained accurately. However, because of the nature of cartridge cases and bullets, the images of striation and impressed marks on their surfaces change radically depending on the incidence direction of light and the type of light source or sources. While marks can be seen very

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clearly under a certain illumination, they can be totally invisible under another. That dependence of visibility on illumination makes the automated matching of evidences by using two-dimensional (2D) image data very difficult. One solution to this problem could be the use of three-dimensional (3D) topography of the surfaces under examination for matching operation, which is independent of illumination and contains the information of marks, provided that it has sufficient spatial resolution.

Balistika, developed at TÜBİTAK-UZAY (Space Technologies Research Institute—former BİLTEN, Information Technologies and Electronics Research Institute), a branch of TÜBİTAK (The Scientific & Technological Research Council of Turkey), is an automated firearms identification system [1]. It uses 3D topographic data for matching the marks on surfaces of cartridge cases and bullets. The earliest work of 3D reconstruction process used for Balistika can be seen in [2]. 3D reconstruction of surfaces of evidences in Balistika is a real life application of Photometric Stereo (PS) [3], which is a depth recovery method, using two or more 2D images of surfaces, taken under some specific illumination conditions. In this study, a 3D data acquisition method of cartridge-cases, based on photometric stereo has been demonstrated.

2. Data acquisition methods for automated firearms identification

Data acquisition is a very important prior step of automated firearms identification. For the highest possible identification performance (and for a successful segmentation of cartridge case base, in particular), an accurate data acquisition method should be used. The data should include all necessary details (marks) and the process should be repeatable (i.e., repeated measurements of the same evidence should lead almost the same result) and insensitive to disturbances (i.e., slight changes in imaging geometry, etc. should not result in significant changes in the measurements).

Data acquisition methods for automated firearms identification can be classified as 2D and 3D methods. “2D data” refers to indirect surface characteristic data measurement, via measuring the surface radiance values of the evidence under examination. “3D data” means actual surface topography obtained from direct or indirect measurements of surface height information. More information about 2D versus 3D data capture can be found in [4].

Data acquisition methods for automated firearms identification based on 2D visual information are available in the literature. For example, in Fireball system [5,6] ring light is used for uniform illumination. In another application [7], sidelight is used for breech face marks and ring light for firing pin impression. Cartridge case images illuminated with spot, diffuse and ring light are demonstrated and compared in [8]. CONDOR system uses a special 2D image acquisition method in order to increase resolution and reduce distortion of digital scans of bullets, including deformed ones [9,10]. IBIS system uses the ring lamp for fired cartridge examination [11]. León [12] proposes an image fusion algorithm in order to get enhanced images by using images illuminated from several directions. Since the images of metallic surfaces of cartridge cases are extremely dependent on the type and geometry of light sources, most methods of 2D data acquisition focus on increasing invariance due to illumination while keeping marks visible in the image as much as possible.

Various other 3D data acquisition methods are also available in the literature. Laser interferometry [13], laser profilometry [14], confocal based sensors [4,15,16], depth from photometric stereo [2], depth from focus [8] and laser conoscopic holography [17] methods are used to construct 3D surface height maps for automatic firearms identification. In a similar manner for automatic comparison of striation marks left by tools like screwdrivers, structured light method is used in [18].

3. Overview of photometric stereo

In CCD or CMOS imaging process, radiance from a surface are measured, whose values depend on properties of radiating sources (i.e., irradiance values on the surface), surface characteristics (i.e., surface reflectance, surface orientation, surface roughness, etc.) and the geometry of the two. Shape and making of a surface play an important role in the reflection of incident rays. Reflectance characteristic of a surface is modeled by Bi-directional Reflectance Distribution Function (BRDF), which is defined in [19] as: “. . ., which tells us how bright a surface appears when viewed from one direction while light falls on it from another”.

There are three reflectance types for an incident ray falling onto a reflecting surface [12]: diffuse (Lambertian), specular and backscatter reflection. If a surface is a perfectly diffuse reflector, i.e., it obeys Lambert Cosine Law which states that the surface radiance is proportional to the inner product of the surface normal and the unit vector showing the direction of the incident ray, it is called a Lambertian surface. More details on this topic can be found in [12,19].

PS is a depth recovery method that uses relationship among the reflectance of surface, radiance vector of illuminating source and the surface normal. PS constructs surface normals using two or more 2D images. In order to solve irradiance equation linearly, at least three images with different illumination directions are necessary.

For Lambertian surfaces, if the number of images with different illuminations, N, equals to 3, the irradiance equation is given as [3]:

$$E = \rho S n, \tag{1}$$

where E is the column vector of irradiance values recorded at a point on the surface, ρ is the albedo (reflectance factor), S is the light source illumination direction matrix and n is the surface normal at that point. If the three vectors in the S matrix are not coplanar [3], then, this equation is solved linearly as

$$\rho = |S^{-1}E| \tag{2}$$